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BRIEF REPORT

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Automatic detection of ineffective triggering and double triggering during mechanical ventilation

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Abstract *Objective:* Imperfect patient–ventilator interaction is common during assisted ventilation, and the detection of clinically relevant mismatching requires visual monitoring of the ventilator screen. We have assessed the feasibility, sensitivity and specificity of an algorithm embedded in a ventilator system that is able to automatically detect the occurrence of ineffective triggering and double triggering in real time. *Design:* Prospective study. *Setting:* Respiratory intensive care unit. *Methods:* Twenty patients undergoing pressure-support ventilation, either non-invasively (NIV, n = 10) or conventionally ventilated (n = 10), were studied. *Measurements:* The detection of ineffective triggering and double triggering from the algorithm was compared by two operators with the "real" occurrence of the phenomena as assessed using the transdiaphragmatic pressure (Pdi). *Results:* Seven of the 20 patients exhibited gross mismatching, while in the remaining patients patient–ventilator mismatching was artificially induced using a pressure control, with a low respiratory rate. Ineffective triggering and double triggering were identified by the operators in 507 and 19 of the 3343 analyzed breaths, respectively. False positives were significantly more frequent in the NIV group than with conventional ventilation. The algorithm had an overall sensitivity of 91% and specificity of 97%. Specificity was statistically higher in the conventional ventilated group than with NIV (99% vs. 95%, $p < 0.05$). *Conclusions:* We have demonstrated the feasibility and efficacy of a new algorithm to detect the occurrence of impaired patient–ventilator interaction during mechanical ventilation in real time. This software may help the clinician in the identification of this problem, which has been shown to have important clinical consequences.

Keywords Patient–ventilator interaction · Pressure-support ventilation · Non-invasive ventilation · Ineffective efforts · COPD

Introduction

It has been shown that poor interaction between the patient and the ventilator, particularly during the inspiratory triggering phase, is associated with an inferior clinical outcome [1, 2].

Theoretically the ventilator should cycle in synchrony with the activity of the patient's respiratory rhythm. Tobin et al. [3] identified four major areas of possible problems in interaction: the triggering of the ventilator, the phase of inspiration after triggering, the passage from inspiration to expiration, and the end of expiration. Precise recordings of the neural timing and the ventilator timing are feasible only employing sophisticated and invasive measurements such as diaphragmatic electromyography (EMG) with the esophageal electrode [4, 5]. However, the occurrence of problems in patient–ventilator interaction specifically during the inspiratory triggering phase may be observed as explicit breath mismatching. The most common and problematic examples of this phenomenon during invasive ventilation are ineffective triggering [1, 2], and double triggering [2, 6]. This type of mismatching can be considered explicit because it may be observed on the flow and pressure traces on the ventilator screen [7] without requiring the greater precision of EMG measurement to support its evidence. However, this requires expertise by the operator in interpreting the events and close visual monitoring.

In the present investigation we validated and tested a non-invasive method targeted to automatically detect the occurrence of some of the major problems of patient–ventilator interaction during the inspiratory triggering phase, namely, ineffective triggering and double triggering.

Methods

Twenty consecutive patients were studied after having signed a written consent to participate in the study that was approved by our local ethics committee.

Patients undergoing NIV were studied while recovering from an episode of acute respiratory failure, while those receiving conventional ventilation were all in an advanced phase of weaning. Patients' characteristics and ventilator settings, as decided by the attending physician, are illustrated in Table 1 of the Electronic Supplementary Material (ESM).

The breathing pattern was measured from the flow signal.

Transdiaphragmatic pressure (Pdi) and the parameters of respiratory mechanics were recorded as described in detail online [8–10].

The occurrence of problems in patient–ventilator interaction were assessed using the Pdi signals (Pdi_{breath}) as a reference [1, 7]. They were then compared with those depicted by the algorithm and recorded as an electrical signal on the recording apparatus (Fig. 1) and as a visual alarm on the ventilator screen.

The types of mismatching were defined as follows [1]:

1. ineffective triggering was identified by a positive Pdi tidal swing not followed by an assisted cycle;
2. double triggering was defined as two cycles separated by a very short expiratory time.

The asynchrony index [2] was defined by the number of asynchrony events divided by the total respiratory rate computed as the sum of the number of ventilator cycles (patient-triggered) and of wasted efforts: asynchrony index (expressed in percentage) = number of asynchrony events / total respiratory rate (ventilator cycles+ineffective triggering) × 100.

Description of the algorithm

The algorithm was designed to detect ineffective triggering as significant perturbations in the expiratory flow signal unaccompanied by a mechanical breath.

Once flow and airway pressure signals have been passed through a noise filter and an unintentional leak compensation algorithm is applied to the flow signal, the first and second derivatives of the flow signal are calculated.

For each perturbation detected, the amplitude and steepness of the decline is used to distinguish ineffective efforts from cardiogenic flow, coughs and swallows. The

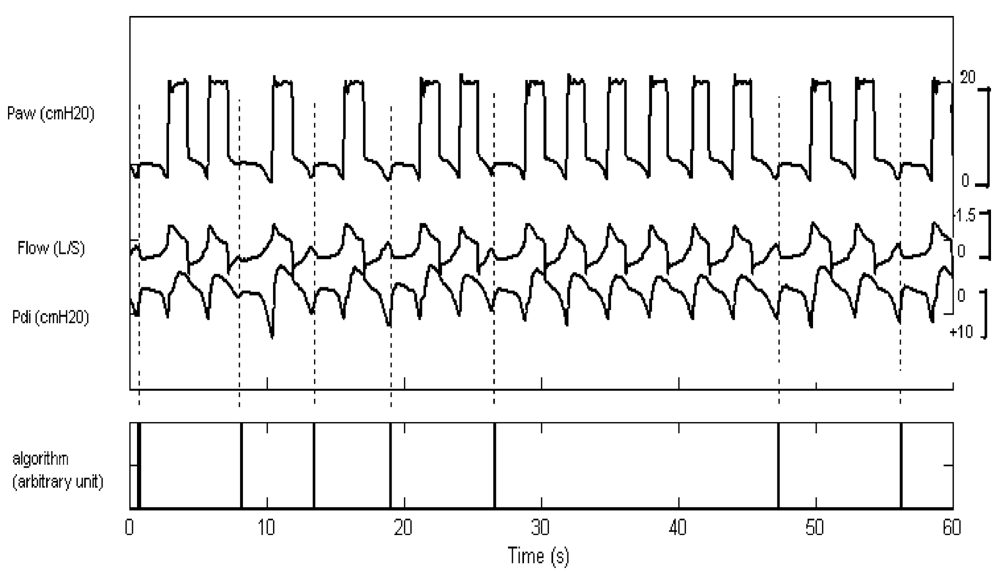

Fig. 1 *Top*: representative traces from a patient showing ineffective efforts during pressure-support ventilation (*Paw*, pressure at the airways opening; *Flow*, airflow; *Pdi*, transdiaphragmatic pressure). *Algorithm*: the electrical trace in volts that depicts the presence of a problem in patient–ventilator interaction

detection algorithm is effective only after 600 ms into expiration following the end of a mechanical breath.

Double triggering was detectable on the airways pressure trace, when a mechanical cycle was followed by another positive cycle separated by less than 500 ms.

Study protocol

All the patients were ventilated with a ResMed VPAP III ST-A ventilator. The algorithm was embedded in a ResMed ResControl II prototype that interfaced to the ventilator and produced a voltage output (0 V to 1 V) of the asynchrony index (1 V representing a positive detection). Patients were using a single-circuit tube with exhalation port.

The physiological data were recorded during a period of 30 min. In 13/20 patients no gross asynchrony index (> 10%) [1, 2, 9] was observed, as described in detail in the online supplement. An additional 10-min trial was performed using pressure control, with a fixed back rate of 10 breaths/min not influenced by any spontaneous inspiratory effort, in order to artificially induce the presence of ineffective triggering.

All signals were collected using a personal computer equipped with an A/D board, and stored at a sampling rate of 100 Hz. A total of 10 min from each of the patients was analyzed. To avoid any potential bias, two blinded investigators performed an independent analysis of the occurrence of explicit patient–ventilator breath mismatching without any visualization on the traces of the electrical signal detecting asynchrony coming from the ventilator.

Statistical analysis

True positives were defined as instances of mismatching detected by the algorithm and identified by the blinded operator on Pdi traces. False positives were those instances of mismatching detected by the algorithm but not by the operator. False negatives were those instances of mismatching detected by the operator but not by the algorithm. Since the number of breaths recorded was different in each patient, sensitivity and specificity were first calculated for each patient using standard formulas [12]. Thereafter we analyzed the mean, SD and 95% CI of each index for all patients. Finally, we analyzed the different distribution in the two groups of patients (i. e. NIV and conventional ventilation) using the Mann–Whitney U test. Correlations between the respiratory mechanics parameters and ventilator settings, and both the occurrence of patient–ventilator mismatching and sensitivity and specificity of the algorithm, were analyzed with Spearman correlation test. All the analyses were performed using Statistica/W statistical package, and $p < 0.05$ was considered statistically significant.

Results

Patient–ventilator mismatching (i. e. asynchrony index > 10%) [1, 2, 11] was identified in 7 (35%) of the 20 patients (four NIV and three using conventional ventilation).

Table 1 shows the ineffective triggering, depicted by standard reference and by the algorithm expressed as percentage of total breaths. False positives were significantly more frequent in the NIV group than with conventional ventilation. Absolute values of ineffective triggering and their percentage distribution according to the modes of ventilation are reported in Table 2 of the ESM.

As shown in Table 2, the algorithm had an overall sensitivity of 91% and specificity of 97% in depicting ineffective triggering. Specificity was statistically significantly higher in the conventionally ventilated group.

Double triggering occurred only 19 times, all but two detected by the algorithm. Therefore, sensitivity was

Table 1 Ineffective triggering and double triggering depicted by standard procedure based on the Pdi and by the algorithm

	CV ($n = 10$)	NIV ($n = 10$)	Total ($n = 20$)	p
Total breaths analyzed per patient (n)	181.1 ± 110.1	137.8 ± 55.3	159.5 ± 87.7	0.28
Ineffective triggering reference method (%)	15.1 ± 9.7	22.7 ± 12.4	18.9 ± 1.5	0.14
Range	0.7–28.7	2.2–51.5		
Double triggering reference method (%)	1.2 ± 1.4	0.7 ± 0.7	0.95 ± 1.1	0.33
True positive detected by algorithm (%)	14.5 ± 9.6	21.4 ± 11.6	17.9 ± 11	0.16
Range	0.2–27.3	2.2–48.5		
False positive detected by algorithm (%)	0.86 ± 0.6	3.8 ± 1.9	2.4 ± 2.1	0.002
Range	0–1.9	0–6.8		
False negative detected by algorithm (%)	0.67 ± 0.6	1.3 ± 0.9	0.98 ± 0.8	0.08
Range	0–1.8	0–3		
True negative detected by algorithm (%)	84.9 ± 9.7	77.3 ± 12.3	81.1 ± 11.5	0.14
Range	71.3–99.2	48.5–97.8		

Data are expressed as percentage of all analyzed breaths. Between-group comparisons were made with the Mann–Whitney *U*-test; *CV*, conventional invasive ventilation; *NIV*, non-invasive ventilation

Table 2 Sensitivity, specificity, positive predictive value and negative predictive value for the ventilator algorithm compared with the standard procedure based on the Pdi

	Sensitivity	Specificity	Positive predictive value	Negative predictive value
CV	87.3 ± 20.8 (72.4–102.2)	99.1 ± 0.6 (98.6–99.5)	83.8 ± 25.2 (65.7–101.9)	99.2 ± 0.7 (98.7–99.7)
NIV	94.7 ± 3.1 (92.5–96.9)	95.1 ± 2.6 (93.3–97)	85.1 ± 8.4 (79.1–91.2)	98.2 ± 1.5 (97.1–99.3)
Total	91.0 ± 15.0 (84–98)	97.1 ± 2.7 (95.8–98.3)	84.4 ± 18.3 (75.9–93)	98.7 ± 1.3 (98.1–99.3)
p	0.28	0.001	0.88	0.78

Due to the small number of double triggerings, data are presented only for the ineffective triggerings (see text for details). Data in parentheses are the 95% confidence intervals. Between-group comparisons were made with the Mann–Whitney *U*-test; *CV*, conventional invasive ventilation; *NIV*, non-invasive ventilation

90.5% and specificity was 100%. Due to the low number of events no statistical analysis was performed for NIV versus conventional ventilation.

As shown in Table 3 of the ESM, the results remained similar when we analyzed separately the subset of patients showing "spontaneous" mismatching and that in which mismatching was induced by the pressure-control ventilation.

No statistically significant correlations were found between the ventilator settings and respiratory mechanics, and either the occurrence of patient/ventilator mismatching or the sensitivity and specificity of the algorithm.

Discussion

It has been shown that up to 25% of ventilated patients exhibit problems of interaction with the ventilator [2] and that this may be associated with an increased duration of ventilation [1, 2].

Unfortunately, the precise detection of asynchrony between the neural inspiratory time and ventilator time relies on sophisticated and invasive methods such as diaphragmatic EMG [4, 5]. Clinically relevant abnormalities in patient–ventilator interaction may be detected on flow and airways pressure traces that showed excellent agreement with those based on Pdi [1, 7], but this requires expert and skilled visual monitoring [7]. Indeed, current technology is unable to alert the clinician in real time of the occurrence of major mismatching during mechanical ventilation.

In this study we have reported the feasibility and accuracy of a new algorithm embedded in a ventilator system and able to detect ineffective triggering and double triggering in real time. These have been shown to be among the major reasons for poor patient–ventilator interaction [1]. The algorithm was not, however, designed to depict problems arising from the recruitment of expiratory muscles during mechanical inflation, or during the switchover point from inspiration to expiration.

We found poor interaction with the ventilator, as defined by an asynchrony index $> 10\%$, in about 35% of the patients, which is in keeping with the data of Thille et al. [2]. Since the aim of this study was to test the accuracy of the algorithm, we induced in the remaining patients the occurrence of ineffective triggering using pressure control, set for a few minutes at the breathing frequency of 10 breath/min. During this mode, the large Pdi swings during a trigger attempt against a closed airway may have increased the amplitude of the "perturbation in the expiratory flow" upon which the algorithm is based, therefore increasing the accuracy of our algorithm. No differences were, however, observed in sensitivity and specificity during pressure-support ventilation and pressure-control ventilation, suggesting reliability of the method under different conditions.

In accordance with this, no statistically significant correlations were found between the sensitivity and specificity and the parameters of respiratory mechanics. The mechanisms underlying poor patient–ventilator interaction have been related to inappropriate ventilator settings (i. e. high level of inspiratory support) or altered respiratory mechanics [1, 2, 13]. This study was not designed to explore this issue; however, we did not find any statistical correlation with the above-mentioned parameters, probably because of the small number of patients showing a mismatching during pressure-support ventilation.

The software that we have developed and tested achieved a good degree of accuracy with high specificity and sensitivity both during conventional ventilation and NIV. We acknowledge, however, that while ineffective efforts and double triggering are recognized as major problems during conventional ventilation, the variety of mismatching during NIV is probably larger and therefore the algorithm may underestimate the problem.

False negatives amounted to 6% and were mainly related to very small inspiratory effort (Pdi $< 2\,cmH_20$), while false positives were statistically significantly more prevalent during NIV. It is possible that the presence of air leaks, swallowing, expiratory muscle recruitment and cardiogenic oscillations may have been responsible for this.

In conclusion, we have demonstrated the feasibility and efficacy of a new algorithm to detect in real time the occurrence of failure to trigger the ventilator and double triggering during both conventional ventilation and NIV. This software, which is specific to the ventilator used, may help the clinician in the early identification of this problem, which has been shown to have important clinical consequences. However the algorithm that we used is not presently designed to assess some specific issues of patient–ventilator interaction encountered during NIV.

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